Develop and Benchmark FDS Numerical Models to Simulate Fundamental Fire Behavior in CLT Structures

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Abstract –

Cross-laminated timber (CLT) is used as the primary structural element for high-rise mass timber buildings. The mass timber buildings that are under construction are largely unprotected as they are not yet equipped with active or passive fire protection systems. With the addition of Types IVA, B, and C, the 2021 International Building Code (IBC) adopted stricter requirements for mass timber buildings that are under construction. However, to date, limited research has been conducted to demonstrate the impact of passive fire protection for CLT buildings that are under construction. To facilitate a better understanding of construction fires and their consequences, it is necessary to develop a numerical modeling solution for the early phases of a CLT construction project, which can be achieved by using building information models (BIM) together with fire dynamics simulation (FDS). Therefore, this study proposes a numerical modeling solution that uses the FDS tool to simulate and assess the fundamental fire behavior in CLT structures. The FDS models are developed and evaluated by benchmarking against the experimental data obtained from compartment fire tests. The FDS analysis results are expected to validate the practicality of simulating the fire behavior in CLT structures using the numerical model proposed in this study. The overarching goal of this study is therefore to develop a comprehensive numerical modeling solution to simulate and assess fires in CLT buildings that are under construction.

Keywords –

Cross-laminated timber (CLT); Building information modeling (BIM); Fire dynamics simulator (FDS); Benchmarking of numerical models.

1 Introduction

Over the past decade, fires have caused significant loss of life and property in timber buildings that are under construction [1]. A 7-story wooden frame building under construction in Oakland caught fire twice in 2017. Similar fires have occurred in other buildings around the country [1]. The leading causes of construction fires are arson or electrical fault and heat sources that are near combustible materials on construction sites. Fire safety planning on a job site is the responsibility of the design team during the design phase of a building. However, traditional fire safety planning relies on frequent manual observations on a job site, which is labor-intensive, time-consuming, and thus highly inefficient. Furthermore, fire safety knowledge is difficult to transfer to people working on site using safety regulations alone [2,3]. Additionally, the development of an effective fire safety plan is often impeded due to designers' inadequate knowledge about jobsite safety procedures as well as limited design-for-safety tools that are available to designers [4].

Mass timber buildings under construction are largely unprotected as they are not yet equipped with active or passive fire protection systems. Multiple floors of those buildings under construction are left exposed since the fire protection can be applied only after the mass timber structural elements are erected. Recently, with the addition of Type IVA, B, and C buildings in the 2021 International Building Code (IBC), the IBC also adopted stricter requirements for fire protection measures of mass timber buildings under construction. Particularly, International Fire Code (IFC) Section 3308.9 requires that at least four stories of any mass timber construction more than six stories above grade is protected with noncombustible material [5]. This stipulation limits the speed of construction and emphasizes the need for data-driven guidelines for mass-timber construction fire safety that has a huge impact on construction labor safety and protection of project-associated property.

Cross-laminated timber (CLT) is commonly used as a primary structural element for high-rise mass timber buildings. However, limited research has been conducted to demonstrate the impact of passive fire protection on a CLT building construction jobsite. To facilitate a better understanding of the behavior of fire within a mass timber building under construction, it is necessary to develop a numerical modeling solution for the early phases of a CLT construction project, which can be achieved using building information models (BIM) together with fire dynamics simulation (FDS). Therefore, this study focuses on the first step of the numerical modeling solution that uses a FDS tool to simulate and assess the fundamental fire behavior in CLT structures.

The remainder of the paper is organized as follows. Section 2 provides a comprehensive review of the relevant literature. Section 3 details the modeling process of FDS models including scenario configurations and essential modeling parameters. This is followed by a numerical implementation and benchmarking of the proposed model. The final section draws conclusions and offers recommendations for future research.

2 Relevant Literature

2.1 Modeling in Construction Fire Safety

BIM has been used to improve construction safety in multiple ways. Li et al. [6] used BIM to improve and optimize safety planning on job sites. Park and Kim [7] proposed a BIM-based quality checking process to assist with eliminating construction safety hazards. Deng et al. [8] developed a BIM-based simulation module to assess the emergency rescue plans for construction accidents and formulate a corresponding emergency management plan. Researchers have also investigated the possibility of using BIM for fire safety. For example, to improve building fire rescue efficiency, Chen et al. [9] proposed an integrated framework integrating BIM together with sensor-based Internet of Things (IoT), Virtual Reality (VR) and Augmented Reality (AR) systems.

However, the research on using BIM in construction fire safety is still in its infancy. Due to the complexity of fire modeling, there are several obstacles to simulating and designing for construction fire emergencies. These complexities include data interoperability as well as the technical limitations of the currently available BIM software that prevents seamless integration with fire dynamics modeling solutions. Therefore, this study proposes a solution that uses a commercially available FDS tool while enabling seamless information exchange with BIM software.

2.2 The FDS Tool for Fire Modeling

PyroSim [10] is a comprehensive FDS software that can be used to simulate fire-driven fluid flows and generate fire dynamics outputs in an efficient manner. The first version of this FDS tool was used by National Institute of Standards and Technology (NIST) and Underwriters Laboratories (UL) in a research program for fire modeling in a building [11]. In their study, the FDS modeling outputs were compared to the full-scale experimental results. Furthermore, they used the FDS modeling outputs to supplement the data collection, including volume flows and air pressures, that were not measured during the experiment. The FDS models were also used to conduct a sensitivity analysis for various testing parameters. In conclusion, FDS for numerical experiments, either as an alternative or complement to traditional experimental fire tests, play an important role for research in fire science [12].

2.3 Numerical Experiments and Traditional Experimental Fire Tests

Full-scale and small-scale experiments have been used with great success to increase the understanding of fire chemistry and fire dynamics in mass timber buildings. Nevertheless, numerical models and simulations are very valuable, particularly when used to complement large-scale tests that are expensive, resource demanding, and time consuming [13]. However, current numerical solutions for mass timber compartment fires have not been benchmarked against data obtained from traditional compartment fire experiments. For example, in [14], fire properties of flammable materials used in the FDS simulation were determined based on the laboratory measurements and validated through fire tests. Similarly, Fernd and Liu [15] assessed their FDS models against the previous experimental work presented in [16] to investigate the effect of different droplet sizes on fire suppression mechanisms. An FDS–finite element method (FEM) simulation approach proposed in [17] was compared to experimental results and used to predict both the thermal and structural responses of a steel column in a fire test. Numerical modeling is a promising approach in fire research. Traditional and numerical experiments are complementary and not competitive. Thus, a combination of these two approaches is necessary to analyze a certain fire phenomenon.

2.4 Motivation and Objectives

FDS is a feasible tool for developing numerical models and simulating the fire behavior in CLT structures because the physical building information can be imported from BIM software into PyroSim seamlessly [18]. However, the numerical modeling technique must be benchmarked against experimental data first to then extrapolate the modeling technique to explore other parameters. Consequently, the scope of this paper is to develop and benchmark a numerical modeling solution against a mid-scale CLT compartment fire test presented in [19] by applying the FDS tool to simulate the fire behavior of CLT panels. In future work, the benchmarked numerical models will be used to conduct analytical parametric tests and to develop and test a BIM-based fire simulation framework for CLT structures under construction.

3 Research Methodology

Figure 1 illustrates the proposed BIM-based simulation framework for modeling the fire behavior in CLT structures under construction. The first task of the framework is to validate the practicality of using the FDS tool together with BIM software for fire dynamics simulation in a building, which was illustrated in our previous work [20]. The second task, detailed in this paper, is to develop and benchmark the proposed numerical models using PyroSim, an FDS software, to simulate the fundamental fire behavior of CLT panels and benchmark the simulations against the experimental data presented in [19]. The second task detailed in this paper details the modeling approach for the numerical experimental configurations and the definition of modeling parameters in the FDS, which will be used to develop the proposed modeling solution for the final task of the simulation framework in future work.

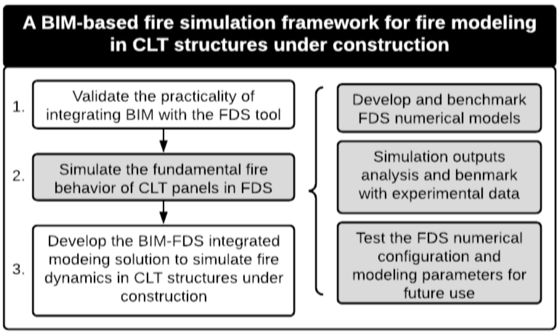

Figure 1 The proposed simulation framework

3.1 FDS Numerical Configuration

The first step of the modeling approach is to develop a 1:1 FDS numerical scenario corresponding to the one presented in [19]. Figure 2 illustrates the FDS scenario for a cuboid numerical compartment developed in PyroSim.

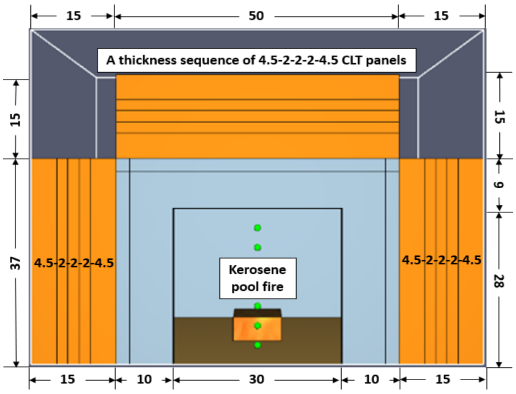

Figure 2 A front view of the FDS scenario (in cm)

The compartment is assumed to be constructed using CLT panels with a thickness sequence of 4.5-2-2-2-4.5 cm and a density of 425 kg/m^3 used in [19]. The numerical compartment has internal dimensions of 50 cm (width) x 50 cm (depth) x 38 cm (height), with a single opening of 30 cm (width) x 28 cm (height). A kerosene pool fire was designed to be continually ignited inside the numerical compartment. Figure 3 shows the numerical compartment walls including the ceiling (C), two lateral walls (LW and LW2), and the back wall (BW). The walls inside the numerical compartment are designed to be covered with two layers of 12 mm Knauf FireShield plasterboards that would not combust in the fire.

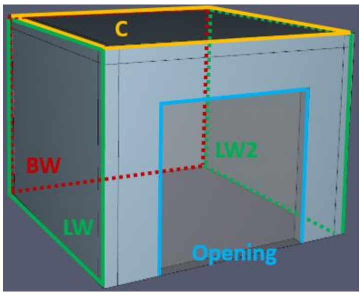

Figure 3 The cuboid numerical compartment

3.2 Modeling Parameters

The thermal properties of the CLT panels and Knauf FireShield plasterboards used in the FDS simulation match the experimental data presented in [19] and are summarized in Table 1. To investigate the effect of exposed CLT area on fire propagation and magnitude, the authors tested eight experimental configurations with varying exposed CLT area matching those in [19]. Table 2 summarizes the FDS numerical configuration matrix with different CLT surfaces exposed to fire. To compute those configurations in FDS, the solution to determine the percentage of various exposed CLT surfaces is calculated as follows (see Equation (1) to (5)):

$$Exposed\ CLT\ area = \frac{\sum A_{CLT,exposed}}{A_{Total}} * 100\% \tag{1}$$

$$A_{Ceiling} = A_{Floor} = 50 * 50 = 2500\ cm^2 \tag{2}$$

$$A_{Wall} = 50 * 37 = 1850\ cm^2 \tag{3}$$

$$A_{Opening} = 30 * 28 = 840\ cm^2 \tag{4}$$

$$\begin{aligned} A_{Total} &= A_{Ceiling} + A_{Floor} + 4A_{Wall} - A_{Opening} \\ &= 11560\ cm^2 \end{aligned} \tag{5}$$

where $\sum A_{CLT,exposed}$ is the sum of area (in cm^2) for exposed CLT surfaces, that are not fire-protected, are treated as fuels in the FDS models.

Table 1 Thermal properties of CLT panels

Material type	Density kg/m^3	Specific heat kJ/(kg·K)	Charring rates mm/s	Pyrolysis rate -	Effect heat of combustion kJ/kg
Yellow pine	425	1.36	0.025	0.7	13

Table 2 FDS numerical configuration matrix

	Configuration	Description	Exposed CLT area cm^2	%
1	Baseline	All CLT surfaces are fire-protected that are not exposed.	0	0
2	Exposed C	The ceiling is exposed to fire.	2500	22
3	Exposed LW	One lateral wall is exposed.	1850	16
4	Exposed LW, C	One lateral wall and the ceiling are exposed.	4350	38
5	Exposed LW, BW	One lateral wall and the back wall are exposed.	3700	32
6	Exposed LW, BW, C	One lateral wall, the back wall, and the ceiling are exposed.	6200	54
7	Exposed LW, BW, LW2	Two lateral walls and the back wall are exposed.	5550	48
8	Exposed ALL	All walls and the ceiling are exposed.	8050	70

3.3 Measurement Devices

To compare the results from the FDS model to the experimental tests conducted in [19], the authors defined output recording locations in the same locations where sensors were located during the experiments in [19]. Figure 4 illustrates the measurement devices and locations created in a three-dimensional (3D) FDS model.

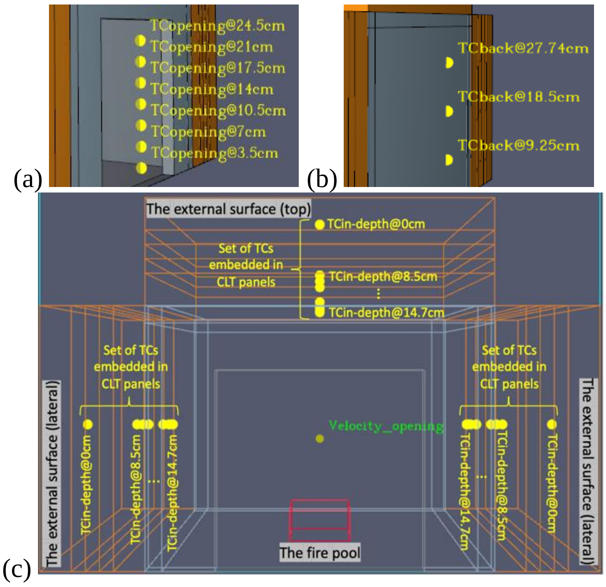

Figure 4 A screenshot of numerical measurement devices of (a) 7 TCs at the opening, (b) 3 TCs at the back wall, and (c) 3 x 8 TCs embedded in CLT panels and one velocity meter at the opening of the compartment (the 3D model (c) is shown in wireframe rendering mode for better viewing)

There are 34 thermocouples (TC) and one velocity meter to measure temperature and air flows respectively. Further details are below:

- 7 TCs are uniformly distributed along the vertical axis of the opening of the numerical compartment at different heights: 3.5 cm, 7 cm, 10.5 cm, 14 cm, 17.5 cm, 21 cm and 24.5 cm above the floor (see Figure 3a);
- 3 TCs are placed along the vertical axis of the back wall (BW) of the numerical compartment at different heights: 9.25 cm, 18.5 cm, and 27.74 cm above the floor (see Figure 3b);
- 3 sets of TCs (8 TCs per set) are embedded in each side wall of constructed CLT panels (the top and two lateral sides) to measure the temperature profile evolution. The depths of each set of TCs with respect to the external surface (not the fire exposed surface) are 0 cm, 8.5 cm, 9.5 cm, 10.5 cm, 13 cm, 14 cm, 14.5 cm and 14.7 cm (see Figure 3c).
- One velocity meter was placed at the opening of the numerical compartment to measure the bi-directional velocities of inflow and outflow (see Figure 3c).

During the simulation, PyroSim writes post-processing simulation outputs as 2D plots of fire dynamics over time including the heat release rate (HRR), flow velocities, and temperature profiles. Those outputs are obtained through the measurement devices defined in FDS numerical models. These numerical models are then used to supplement the observations of fire dynamics through 3D animations. Besides, the cell size of FDS numerical models is defined as 1 mm to obtain reliable and accurate simulation outputs without increasing the computational time exponentially. The details of the numerical tests are included in the following section that discusses the analysis and benchmarking of FDS numerical models.

4 Simulation Outputs and Benchmark

4.1 Overview

This study conducts an FDS analysis to benchmark the proposed numerical modeling approach using the data measured experimentally in [19]. The research results presented in this section demonstrates that the proposed modeling approach is correlates well with experimental measurements and confirms relevant experimental findings. Particularly, three major experimental findings of [19], that are summarized next, are evaluated: (1) CLT panels contribute significantly to the total heat release of the fire, (2) the presence of a ceiling increases the flow velocities of fire spread, and (3) the internal temperature of the compartment does not necessarily increase with the increase of the exposed area. The validation of the study results aims to provide a modeling solution basis, including FDS numerical configuration and modeling parameters, towards the proposed simulation framework for modeling the fire behavior in CLT structures.

4.2 Heat Release Rate

Figure 5 illustrates the comparison of HRR between the FDS numerical outputs and the experimental results obtained in [19].

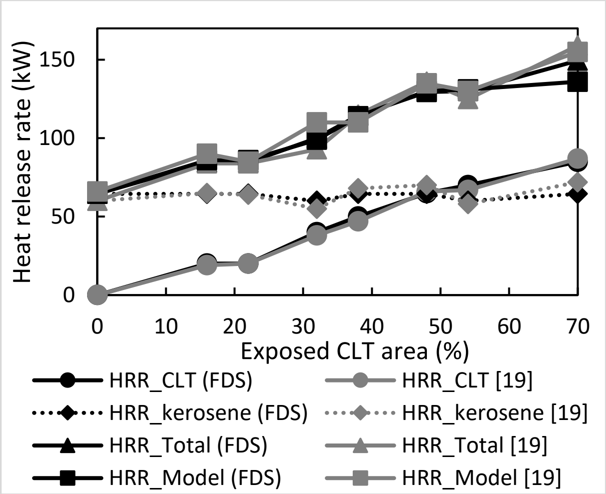

Figure 5 The comparison of HRR between FDS outputs (in black color) vs Gorska et al. [19] (in grey color)

The FDS outputs of HRR, computed in numerical models, corresponds to the HRR of experimental data for different sources. Figure 5 shows the comparison of different HRRs from [19] compared with those predicted by the FDS model, including the HRR contributed from the CLT (HRR_{CLT}), kerosene ($HRR_{kerosene}$), the summation of the HRR from the CLT and the kerosene (HRR_{Total}), and total HRR measured during the test (either in [19] or FDS model) (HRR_{Model}). Particularly, HRR_{Model} was used to determine if there were HRR losses within the compartment during the experiments in [19] by comparing HRR_{Model} to HRR_{Total}. As shown in Figure 5, the experimental result of $HRR_{Model[19]}$ in [19] has a satisfying prediction of $HRR_{Total[19]}$ (grey lines); in FDS numerical models, both $HRR_{CLT(FDS)}$ and $HRR_{Kerosene(FDS)}$ contribute to $HRR_{Model(FDS)}$, with satisfying computational results for $HRR_{Total(FDS)}$ (black lines). Furthermore, the fact that CLT panels contribute significantly to HRR_{Total}, as demonstrated in [19], is confirmed in the FDS analysis as it corresponds to the trend of HRR_{CLT} with varied exposed CLT area.

4.3 Flow Velocities at the Opening

The flow velocities at the compartment opening as a function of the exposed CLT area are shown in Figure 6. These flow velocities compare the numerical output to the experimentally measured flow velocities.

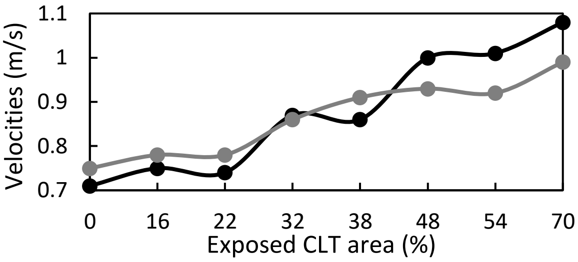

Figure 6 Computed flow velocities (in black color) at the compartment opening for different configurations compared to Gorska et al. [19] (in grey color)

To conclude, the numerical model can predict the flow velocity trend obtained in [19] reasonably well as seen in Figure 6; the flow velocities increase as the exposed area increases. The increase in velocities is due to the mass flow exchange driven by burning CLT panels; hence, all CLT surfaces exposed to fire would increase the flow velocities.

Additionally, the presence of an exposed CLT ceiling increases the velocity of the fire spread compared to other exposed surfaces with similar surface area. This finding aligns with the second finding in [19]. This can be due to CLT ceiling's exposure causing heat loss, which is released through the upper boundary of the numerical compartment. This behavior also implies that CLT panels' burning rate is not only associated with the area of exposed surfaces but also with their location, e.g., ceiling vs. vertical walls.

4.4 Gas-phase Temperature Profiles

Figure 7 presents the mean gas-phase temperature (°C) measured at different heights (m) and at different locations of the compartment for all test configurations in [19]. The x-axis is the mean gas-phase temperature, and the y-axis is the height of the compartment. Each test configuration has varying CLT exposed surfaces. As stated in the previous section, both the area and the location of exposed CLT surfaces affect the burning rate.

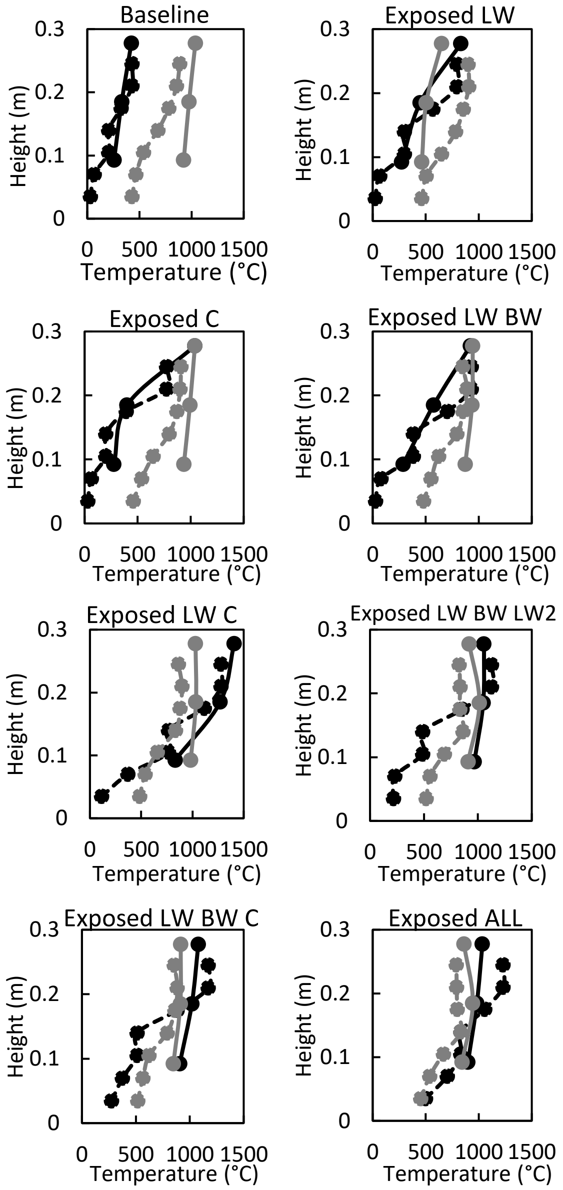

Figure 7 Gas-phase temperature profiles against heights inside the compartment (solid lines) and at the opening of the compartment (dashed lines) compared to the results obtained in Gorska et al. [19] (in grey color)

As shown in Figure 7, the curve trend of measured temperatures in FDS numerical models support the temperature profiles measured experimentally in [19]. Referring to [19], the internal temperatures of the compartment are not necessarily higher when the exposed surface area is larger; however, in FDS numerical models, more exposed CLT surfaces indicate higher temperatures both inside and at the opening of the compartment compared to the measured values in [19]. This is possibly due to the thermal properties of FireShield plasterboards that are defined as non-combustible in FDS models, hence prevent fireproofing applied CLT panels from burning immediately.

Essentially, both the burning of combustible elements and the external heat flow can impact the internal temperature of the compartment. Referring to [19], the excess of pyrolysis gases from the burning panels is expected to induce an increase in external heat release rate due to a potential growth of the external flames. Hence, future research should investigate the effect of massive heat flow, which may trigger the collapse of plasterboards and ignite fireproofing applied CLT panels that would raise the internal temperature of the compartment.

In addition, the evaluation of the temperature profiles indicates a thermal gradient within the CLT panels themselves with higher temperatures on the surface of the CLT panels exposed to the fire. It can be observed from Figure 8 shows that the temperature of the CLT increases with increasing depth into the CLT from the external surface to the fire exposed surface. The data shown also indicates that at the depth of 14.5 cm away from the external surface, the thermal gradient levels off and the temperature slightly decreases while the CLT panels start to char.

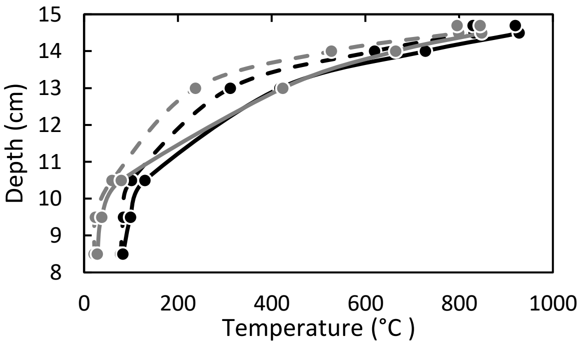

Figure 8 Linear temperature profiles in the CLT panels at 15 mins (dashed lines) and 20 mins (solid lines) after flashover compared to Gorska et al. [19] (in grey color)

4.5 3D Animations for Fire Dynamics

In addition to the HRR, flow velocities, and temperature at different elevations of the CLT compartment, the numerical simulations can provide additional information that cannot be obtained through an experiment. First, the numerical simulations can provide additional insights into the fire dynamics in the compartment through 3D animations that can supplement the observations on fire dynamics from the test. Figure 9 is an example of 3D Smokeview for fire dynamics for "Exposed C" configuration. It shows that the CLT panels are burned away over time.

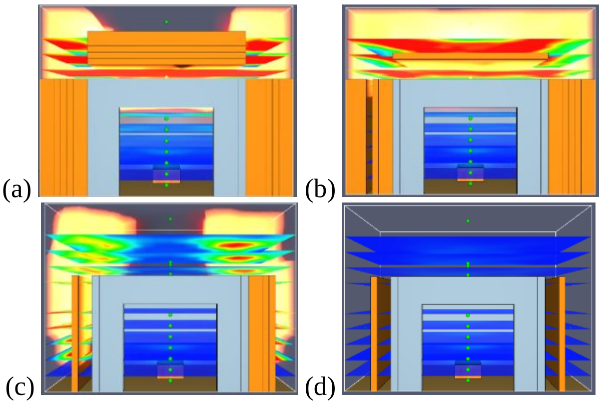

Figure 9 An example of 3D Smokeview for fire dynamics at the simulation time of (a) 400 seconds, (b) 600 seconds, (c) 1200 seconds, and (d) 1800 seconds.

In addition, a numerical model enables users to collect time dependent information about fire dynamics at any location. During a fire test, it is difficult to collect real-time observational data that can inform researchers about the fire development and progression. Images, such as those shown in Figure 9, can supplement photos and videos taken during a fire test that may be skewed or difficult to interpret due to elevated temperatures.

The second way these numerical models can supplement experimental data is through additional temperature measurements. Experimental data quantities are limited by the capacity of the laboratory's data acquisition system. This capacity is often limiting for the number of measurements that can be taken throughout the test. The FDS models described in this paper can output infinite amounts of temperature data, thereby allowing researchers to obtain additional temperature measurements.

Lastly, large-scale compartment fire tests are costly and time consuming. Benchmarked FDS models, such as those described in this paper, allow for researchers to adjust modeling parameters in numerical models to support conducting parametric experiments that are valuable for fire science research, particularly when the corresponding large-scale tests are expensive, resource demanding, and time consuming.

To conclude, the main advantage of numerical experiments is being more resource efficient compared to traditional experimental fire tests. With an appropriate level of control of the experiment, several numerical experiments can be carried out through computational tools at a time.

5 Summary and Future Research

Construction fires are a big threat to construction worker safety and property loss. To date, several studies have demonstrated the impact of passive fire protection on a job site for CLT construction. To develop a BIM-based simulation framework for modeling the fundamental fire behavior in CLT structures, the FDS tool, that is interoperable with BIM software, can be used to simulate fire dynamics efficiently. Hence, this study provides a modeling solution that uses PyroSim, an FDS program, to simulate and benchmark the fire behavior in CLT structures regarding HRR, flow velocities, and temperature profiles in a numerical compartment model. The FDS numerical models are benchmarked with previous experimental configurations as well as data measured experimentally in [19].

To conclude, the numerical outputs support the data measured experimentally and confirm the three major experimental findings of CLT burning phenomenon tested in [19] including: (1) the CLT panels contribute significantly to the total heat release of the fire, (2) the presence of a ceiling increases the burning rate at a higher rate compared to other exposed CLT surfaces, and (3) the internal temperature of the compartment is not necessarily higher when the total exposed area is larger. Additionally, this study provides FDS outputs that can supplement the experimental tests and observations including 3D animations of the fire spread. Such animations provide a better view of numerical modeling outputs that can be utilized for multiple purposes regarding fire safety, such as transferring knowledge about fire behavior of building materials or enhancing construction fire safety education. Therefore, the validation of numerical results in this paper confirms the practicality of modeling the fire behavior in CLT structures using FDS numerical models. The FDS numerical configuration and modeling parameters will be implemented in the next step of this study to simulate and assess fires in CLT buildings that are under construction.

There are several limitations to this study which should be investigated in future research. First, there are limited number of publications presenting the results of compartment fire tests for CLT structures. To improve the reliability of FDS numerical models, experimental data from multiple sources can be used for benchmarking. Second, the numerical models in this study simulate the fundamental fire behavior of CLT panels in a mid-scale compartment. However, the burning behavior of large CLT structures could be different. Thus, this phenomenon should be further studied. Third, due to the complexity of fires, the influential factors of fire dynamics in a building are complex, hence, the modeling parameters should be investigated in detail when developing the numerical models. In addition to the modeling parameters tested in this study, future research should provide additional insights regarding a CLT structure fire, e.g., the effect of external heat flows, the charring phenomenon among others.

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